NASA TECHNICAL MEMORANDUM

NASA TM X-73,162

(NASA-TM-X-73162) STUDY OF A VERY LOW COST AIR COMBAT MANEUVERING TRAINER AIRCRAFT (NASA) 29 p HC $4.00 CSCL 01C

N76-33190

Unclas

G3/05 07954

NASA TM X-73,162

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August 1976

1. Report No. NASA TM X-73,162	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STUDY OF A VERY LOW COST AIR COMBAT MANEUVERING TRAINER AIRCRAFT		5. Report Date
		6. Performing Organization Code
7. Author(s) Gary C. Hill and Jeffrey V. Bowles		8. Performing Organization Report No. A-6724
9. Performing Organization Name and Address NASA Ames Research Center Moffett Field, CA 94035		10. Work Unit No. 791-40-03
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A very low cost aircraft for performing Air Combat Maneuvering (ACM) training was studied using the BD-5J sport plane as a point of departure. The installation of a larger engine and increased fuel capacity were required to meet the performance and mission objectives. Reduced wing area increased the simulation of the ACM engagement, and a comparison with current tactical aircraft is presented. Other factors affecting the training transfer are considered analytically, but a flight evaluation is recommended to determine the concept utility.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
ACM Training, ACM Simulation, BD-5J	STAR Category - 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	28	$3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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INTRODUCTION

In response to USAF Flight Dynamics Laboratory (FDL) interest in a very low cost Air Combat Maneuvering Trainer (ACMT) aircraft, the Research Aircraft Technology Office of the NASA Ames Research Center has performed this study of an aircraft with performance capabilities and minimum cost for ACM training. The BD-5J aircraft is used as the point of departure, first considering configuration options, then design modifications. The Ames-developed General Aviation Synthesis Program (GASP) (ref. 1) was used for determining the relationships of weight, cost, and performance.

This study shows that considerable departure from the BD-5J design is necessary to meet the selected design criteria but that an aircraft of this class (size and weight) can meet the performance required for ACM training. The final aircraft design incorporates a larger engine and has a lengthened fuselage to accommodate the increased fuel required by the larger engine and to maintain center of gravity location. The wing area is reduced to enhance "fighter-like" performance, but the layout (structure, systems, wing planform, etc.) remains the same. If one chooses to consider the final design aircraft of this study as a derivative aircraft, the modifications are extensive. However, these modifications would be considerably less expensive than development of an entirely new aircraft.

The extent to which an ACMT aircraft could simulate the actual ACM environment and be useful for training would have to be evaluated by any potential user. Some analytic considerations of the viability of applica-

tion are made in the last section of this report entitled Training Transferability. Greatest utility will most likely be found in the teaching phase or as a supplement to, rather than as a substitute for, operational training.

MISSION ANALYSIS

Mission and performance criteria were established in accordance with the guidelines formulated by the USAF Flight Dynamics Laboratory (Ref. 2). The ACMT design mission is detailed in the profile shown in figure 1. It is essentially a flight of 50 n. mi. to and from the training area, 1 hr of ACM training time, and a landing reserve of 5% of the takeoff fuel. All mission segments are performed at optimum speeds (e.g., climb and cruise at best fuel economy speed), and the ACM fuel penalty is calculated at the speed that maximizes the sustained normal load factor. The maneuver performance is also stated in terms of maximum sustained load factor. The conditions selected for computing the maneuver turn performance are 1534 m (5000 ft) altitude, best turn speed, maximum continuous power, and 60% fuel. A sustained turn capability of 4 g was desired. Cost goals of $50,000 acquisition and $50 per hour operating were also sought.

STANDARD BD-5J PERFORMANCE

The BD-5J as pictured in figure 2 was used as the baseline for this study. The performance of the BD-5J aircraft flying the ACMT mission profile was calculated and tabulated in Table I. The 107.5 kg (237 lbs) of fuel available for ACM provides 1 hr 28 min of combat time at the maximum continuous power setting.

Table I - BD-5J Flying ACMT Mission Profile

Leg	Fuel, kg (lb)	Distance, n. mi.	Fuel flow, kg/hr (lb/hr)	Time, min	Speed, knots
Taxi	3.4 (7.5)	0	20.41 (45)	10	0
Takeoff	1.59 (3.5)	0	113.4 (250)	1.2	67.8
Climb	6.99 (15.4)	13	83.7 (184.5)	5	189
Cruise	10.57 (23.3)	37	54 (119)	12	189
Combat	107.5 (237.0)	0	73.44 (161.9)	88	189
Cruise	14.29 (31.5)	50	54 (119)	16	189
Reserves	7.6 (16.75)	0	--	--	--

The thrust that would be required to match the drag created at load factors of 2, 2.5, 3, and 3.5 g is shown plotted against airspeed for the BD-5J aircraft in figure 3 (solid lines). The amount of thrust that is available, as shown by the boundary line, indicates that the maximum sustained load factor is less than 2.5 g, far below the desired 4.0-g level.

The excess 28 min of combat time fuel represents a performance weight penalty that could be converted to better performance by loading only enough fuel to meet the 1 hr combat time requirement. The decrease in required thrust (drag), achieved by off loading 36.3 kg (80 lbs) of fuel to match the ACMT mission model's 1 hr of combat time, is shown by the dashed lines in figure 3. The sustainable load factor is improved to better than 2.5 g by the lighter fuel load, but the improvement is not sufficient to meet the desired goal.

MODIFIED BD-5J PERFORMANCE

Wing Loading Modification

The next design modification to be considered was variation of the wing loading by changing the wing area. This can be done relatively easily for the BD-5J aircraft since wing removal is accomplished with the removal of four bolts, and the manufacturer presently has several wing options available. The variation on wing loading used in this study assumes constant wing geometry (aspect ratio, taper, airfoil section), so the results reflect only changes in wing area. They do not represent the actual family of wings which Bede has built, nor are they a full design scaled by wing loading, nor are they an optimization of the wing geometry.

Figure 4 illustrates how the design cruise speed was determined for the different wing loadings. The criterion is minimum fuel required to achieve the design mission profile of figure 1, not best cruise economy. As the wing loading is increased by reducing the wing area, the volume available for wing fuel tanks is also reduced. A fuel volume constraint is imposed at the point where the wing becomes so small that there is insufficient fuel to perform the mission. The effect of wing loading on the top speed is also shown by the upper constraint line on figure 4.

Just as the wing loading affects the optimum cruise speed, it also affects the speed at which maximum normal load factor can be sustained. The thrust required to sustain various normal load factors is shown in figure 5 in a manner similar to figure 3. Each variation in wing loading is computed by fixing the wing area and then deriving the aircraft weight that results from the new wing weight and the fuel required to meet the design mission.

Because the sustained maneuverability load factor is computed at an optimum airspeed, we are interested only in the minimum values of thrust required (drag) for each wing loading. These values are cross-plotted as thrust required versus wing loading in figure 6. The takeoff wing loading of the BD-5J aircraft fueled to meet the ACMT mission is indicated by the arrow in the figure, and it is evident that little sustained load factor performance improvement could be expected from changing the wing size.

Thrust Loading Modifications

From the previous analysis, it was concluded that aerodynamic improvements alone would not achieve both the desired mission and performance goals. After researching the inventory of small turbine engines, the Williams Research WR19-3 axial flow turbofan engine was selected as a candidate of suitable size and cycle for this mission. The engine is a man-rated version of the F-107 SCAD missile engine. It has a static rating of 2535.5 N (570 lb) thrust and has a fan bypass ratio of approximately unity. Engine performance data was supplied by Williams Research Company of Walled Lake, Michigan (Ref. 3).

The installation of the WR19-3 engine in the BD-5 aircraft is illustrated in figure 7. The engine compartment acts as a plenum from which the air is drawn into the engine. A bellmouth lip is fitted to the engine face to minimize distortion to the engine. Baffles may also be required for the same purpose. The 57.5 liter (15.2 gal) fuselage fuel tank was removed to provide additional space around the engine face and ensure adequate air flow.

The inlets are also modified to accommodate the increased mass flow of the more powerful engine and to diffuse the incoming flow to a minimum Mach number to enhance the efficiency of the plenum inlet. The plenum inlet was selected because it required minimum airframe modifications; however, compared to ram

recovery inlets it is relatively inefficient. The pressure recovery schedule computed for this analysis is plotted in figure 8. At maneuver conditions, a thrust loss of approximately 15% is incurred. Despite these losses, the engine is of sufficient size that performance goals can still be accomplished.

In addition to utilizing the area formerly occupied by the internal fuel tank, the installation of the heavier WR19-3 engine created a nose-up pitching moment. Note that the BD-5J aircraft is already aft center of gravity (c.g.) critical and has 15.88 kg (35 lb) of ballast in the nose. Both the c.g. and fuel volume problems were solved with an extension of the fuselage ahead of the firewall. The length of the fuselage "plug" is determined by the length required to: (1) return the c.g. back to its original position relative to the aerodynamic chord, and (2) provide sufficient fuel volume to accomplish the design mission. The fuselage extension is not without precedent, as Bede Micro of San Jose, CA, has incorporated a 5.2-in extension into some 250 propeller-driven BD-5 aircraft to accommodate a Honda engine or long-legged pilots. With the larger engine and a fuselage "plug" of 22.89 cm (9 in) the mission takeoff gross weight was raised to 537.51 kg (1185 lb). Ballast amounting to 6.8 kg (15 lb) was removed from the nose in order to maintain the c.g. location relative to the aerodynamic chord with the extended fuselage.

From the plot of thrust required and available for the re-engined BD-5 aircraft shown in figure 9, it can be seen that the sustained maneuver load factor exceeds the desired 4.0 g by 0.5 g. Both the design mission range and the maneuver performance goals are now achieved with this configuration. The maximum level speed is estimated to be 350 knots at 1524 m (5000 ft) altitude.

FINAL DESIGN

The maximum sustained turn capability is an important measure of ACM performance, but the specific excess energy versus turn rate curve as used by Lt. Col. John Boyd (ref. 2) tells a more complete story. Specific excess energy is defined by Boyd as:

$$P_S = \frac{(T - D)}{W} V$$

When the maneuver speed V and weight W are fixed at a given altitude and power setting T, only the drag D will change with load factor. Figure 10 gives an example of the specific excess energy (P_S) curve plotted against load factor and notes some of the significant points on it. Air Combat Maneuvering tactics exploit points along this curve, and not just the $P_S = 0$ point where the load factor is sustained with no loss in altitude or airspeed.

Reference 4 is a report on a flight test of the BD-5J aircraft conducted at the USAF Test Pilots School, Edwards Air Force Base, CA. A portion of this report is quoted as follows: ". . .maneuvers in or near the vertical plane definitely showed geometric degradation when compared with UE (unit equipment) aircraft under similar conditions. BFM (basic fighter maneuvers) events performed in or near the vertical plane caused large energy losses. . . ."

How can the balance of vertical versus horizontal maneuverability be altered? Most easily by changes in wing loading. By decreasing wing area, gains are achieved in vertical maneuvering capability but at a sacrifice of horizontal maneuverability as measured by maximum sustained and instantaneous turn capability. The final design sought to exploit the excess sustained turn capability of the over-sized engine to achieve better vertical maneuverability by reducing the wing area to match the thrust available and the thrust required for the 4.0 g sustained turn. In reducing the wing area it was necessary to

increase the fuselage length even further to 24.64 cm (9.7 in) because, as fuel volume available in the wing decreased, it had to be displaced to the fuselage. The added fuselage length allowed the removal of the full 15.88 kg (35 lb) of ballast from the nose, and permitted the cavity below the engine and behind the main landing gear stowage to be used for additional fuel while maintaining the same center of gravity location. The engine installation in figure 7 illustrates all of these modifications. The removal of ballast weight and better cruise economy of the higher wing loading benefited performance.

The plot of P_S versus load factor in figure 11 shows the performance advantages of the reduced wing area. The wing loading at takeoff for the final design is approximately that of modern fighter aircraft. Practical limits of maintaining balance without relocating the wing, providing fuel volume, and maintaining a reasonable landing speed governed the extent to which the wing area could be reduced. The increased 1 g P_S, which is an increase in acceleration and climb capability, resulted from sacrificing turn capability by reducing the wing area and flying at a speed that maximizes the 1 g specific excess energy, while still meeting the 4.0 sustained g capability.

Specifications of the final design are given in Table II, and an illustration is shown in figure 12.

Table II - Specifications of the Final Design

Weight (gross)	514.8 kg	(1135 lb)
" (0.6 fuel)	447.4 kg	(986 lb)
" (empty)	257.2 kg	(567 lb)
Fuselage Length	4.07 m	(13.35 ft)
Wing Span	4.4 m	(14.4 ft)
Overall Height	1.86 m	(6.1 ft)
Thrust (uninstalled)	2535.5 N	(570 lb)
" (installed - SLS)	1926 N	(433. lb)
Maximum speed	375 knots	
Landing distance	632.8 m	(2076 ft)
Approach speed	100 knots	
Takeoff distance	652.3 m	(2140 ft)

Reducing the wing area while maintaining wing fuel capacity constant by appropriate changes to the wing geometry was also studied. A key parameter in determining the fuel capacity of the wing is the aspect ratio. As the aspect ratio was reduced, higher induced drag increased the fuel requirement at approximately the same rate at which higher wing loading reduced the fuel requirement. It was concluded that shifting fuel to the fuselage was a more viable solution.

Cost factors are significant in considering the ACMT and its ability to simulate rather than duplicate the ACM engagement. Estimates of operating and acquisition costs have been computed by GASP and are shown in Table III. They are based on an accounting system appropriate to general aviation rather than military operations; however, they can provide a relative measure of costs.

Table III - Cost Estimates

Aircraft	Acquisition Single buy, $	 Production run, $	Operating $/hr
BD-5J	20 K	35 K	13
(TRS-18)	18 K		
BD-5	53 K	20 K	27.4
(WR19-3)	150 K	60 K	
Final Design	60 K	20 K	26.6
(WR19-3)	150 K	60 K	

TRAINING TRANSFER

The full capabilities of a high-performance, Mach 2+ fighter are not going to be duplicated nor are they desired, as they would negate the cost savings of the trainer. Keeping fully combat ready aircraft available for training complements the ready force, while trainers do not. The very low cost ACM

trainer does simulate many aspects of the ACM environment such as spacial orientation, pilot control responses, visual cues, g loadings, and the realism of flight. It would not duplicat· ·he handling qualities nor the weapons system of the full-sized aircraft, but it would provide a greater degree of simulation than ground-based simulators.

Specific excess energy values for typical fighter aircraft are an order of magnitude greater than could ever be achieved by a "micro" aircraft because of the higher speed of the actual combat arena. If velocity is divided out of P_S, the climb angle that could be sustained by that excess energy is derived. The P_S of a 300-knot ACMT could not compare to that of a Mach 2+ fighter. However, ACM maneuverability can be simulated by scaling nondimensional measures such as climb angles and load factors and by balancing the vertical and horizontal maneuvering performance.

This conceptual design study has shown what could be accomplished with a present-day airframe and engine in designing an ACMT aircraft to achieve the specified mission and performance requirements. Figure 13 compares the sustained climb angle versus turn rate of a popular twin-engine fighter, a single-engine attack aircraft also used by both services, and the final ACMT design. The extreme values of sustained climb angle attained by fighter aircraft are mainly due to the thrust augmentation (after burner). This aspect of figure 12 makes it an "oranges and apples" comparison. The ACMT and the attack aircraft have similar ACM persistence, while with the same reserves and radius, the fighter would have less than 15 min endurance at the conditions given ACM because of its extremely high fuel usage rate with augmented thrust.

To our knowledge, tests or studies have not been performed to quantify what variables are important in scaling the transonic ACM down to the 200-300 knots regime. Certainly balancing the ratio of vertical to horizontal maneuvering, as

just discussed, is significant. Visual cues of distance will be similar as illustrated in figure 14. This is particularly important since one of the major aspects of ACM is the judging of relative distance, position, orientation, and closure rates.

Another factor of similarity is the angular turn rates of the ACMT and the fighter operating at faster speeds but at greater turn radii. The angular turn rates, which are the product of the velocity and the radius, are illustrated in figure 15 by the magnitude of the angles. The scaling is not so exact as in the case of distance perception. The difference in angular turn rate, though degrading the simulation, may be an advantage for training. Maneuvers would develop more quickly, forcing quicker reaction and judgement times and allowing more engagements to be performed in an allotted time. There are factors such as these that are beyond analysis and would require a test program to adequately evaluate.

The ACM trainer aircraft concept also contains the possibilities of training in aircraft of differing thrust and wing loading. Exploiting advantages in turn, acceleration, and climb capability is at the heart of ACM and is not usually available when operating in aircraft of one type. Except in the training situation, ACM rarely takes place between aircraft of equal performance characteristics; advanced ACM training involves learning to exploit areas of advantage, whether they be superior turn, acceleration, or climb capabilities. The very low cost ACMT not only provides lower cost advantages for training, but also the advantage of dissimilar aircraft ACM training, while maintaining only one aircraft type. The areas of advantage and disadvantage of known-threat fighters could be duplicated by tailoring the shape of the P_S curve similar to what was done in figure 11 to enhance the performance similarities to tactical aircraft.

CONCLUSIONS

This study has attempted to develop an aircraft for use as an Air Combat Maneuvering Trainer using the BD-5J sport plane as a point of departure. The design objectives were not attainable through aerodynamic modifications alone, and required the installation of a larger engine. The selected engine compromised the design by being oversized but was the best for which data was available. Although the combat maneuverability performance goal in terms of sustain load factor was achieved, the full vertical and horizontal performances of modern fighter aircraft were not reached.

The very low cost ACMT aircraft could be used to conduct meaningful ACM training at a substantial cost savings. No speculation has been made as to the viability of this concept in a basic training or operational training environment. Surely the degree to which ACM can be simulated, either airborne or ground based, rises proportionately to the cost until at 100% realism, the cost of operating the combat aircraft for training is reached. The acceptable point short of full realism where significant training can still be accomplished remains to be defined. Hopefully, this study will provide inputs as to what can be accomplished for the persons who must make those decisions.

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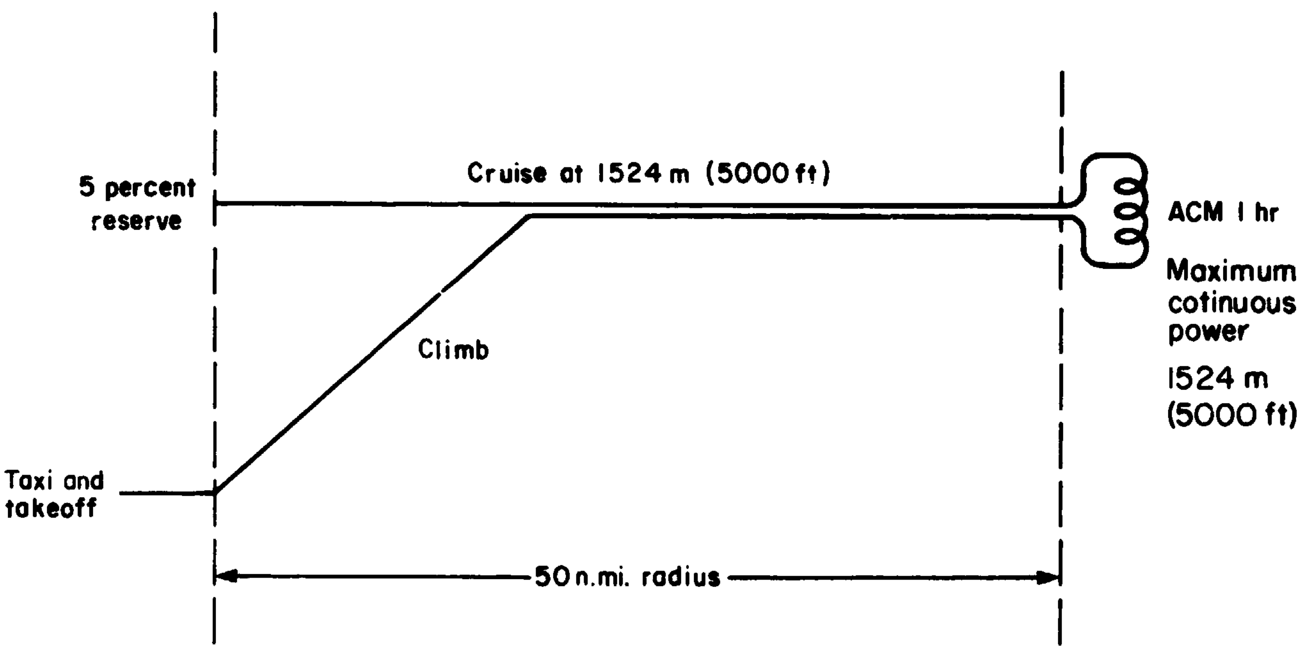

Figure 1.- Low-cost Air Combat Maneuvering Trainer (ACMT) design mission.

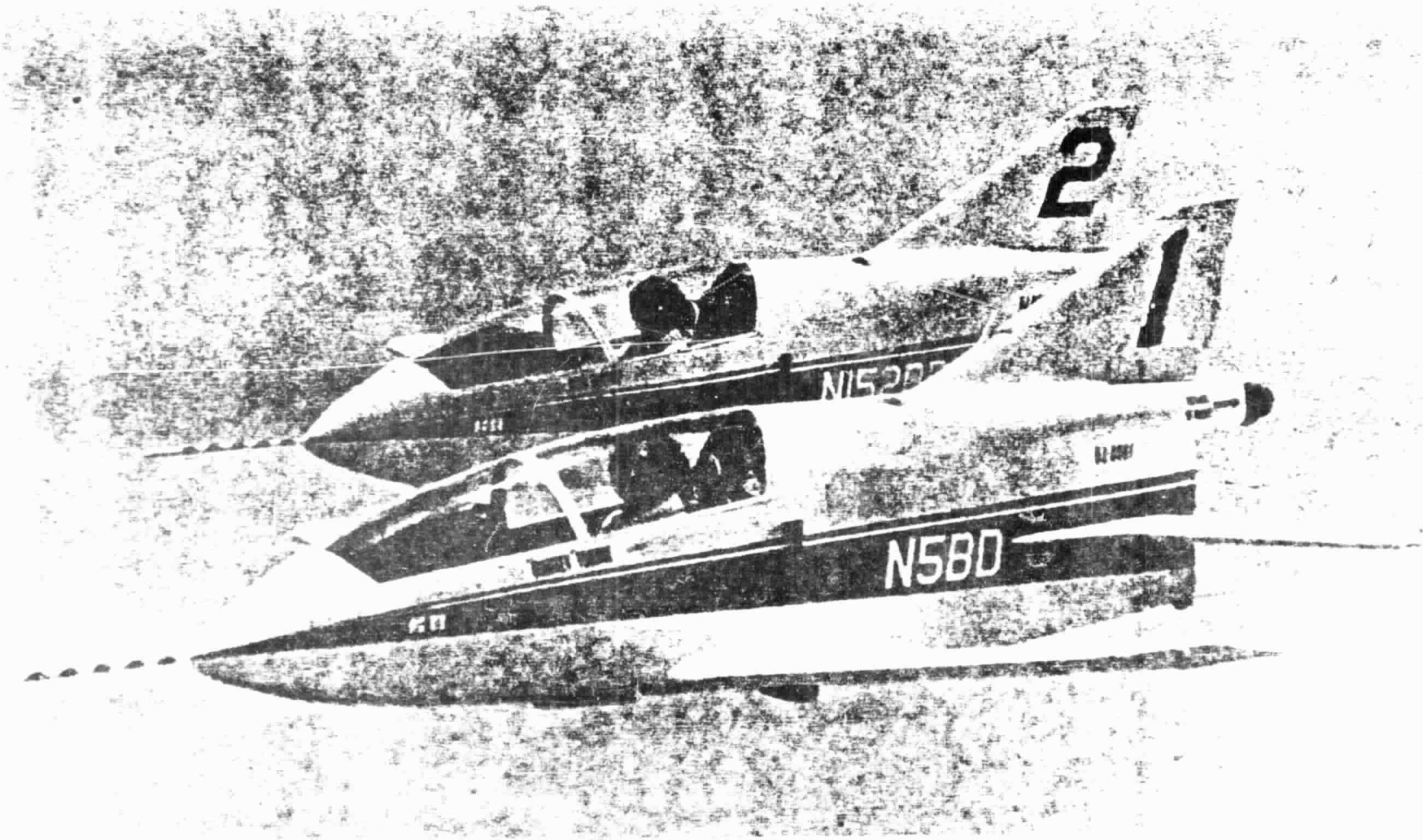

Figure 2.- BD-5J flight demonstration team.

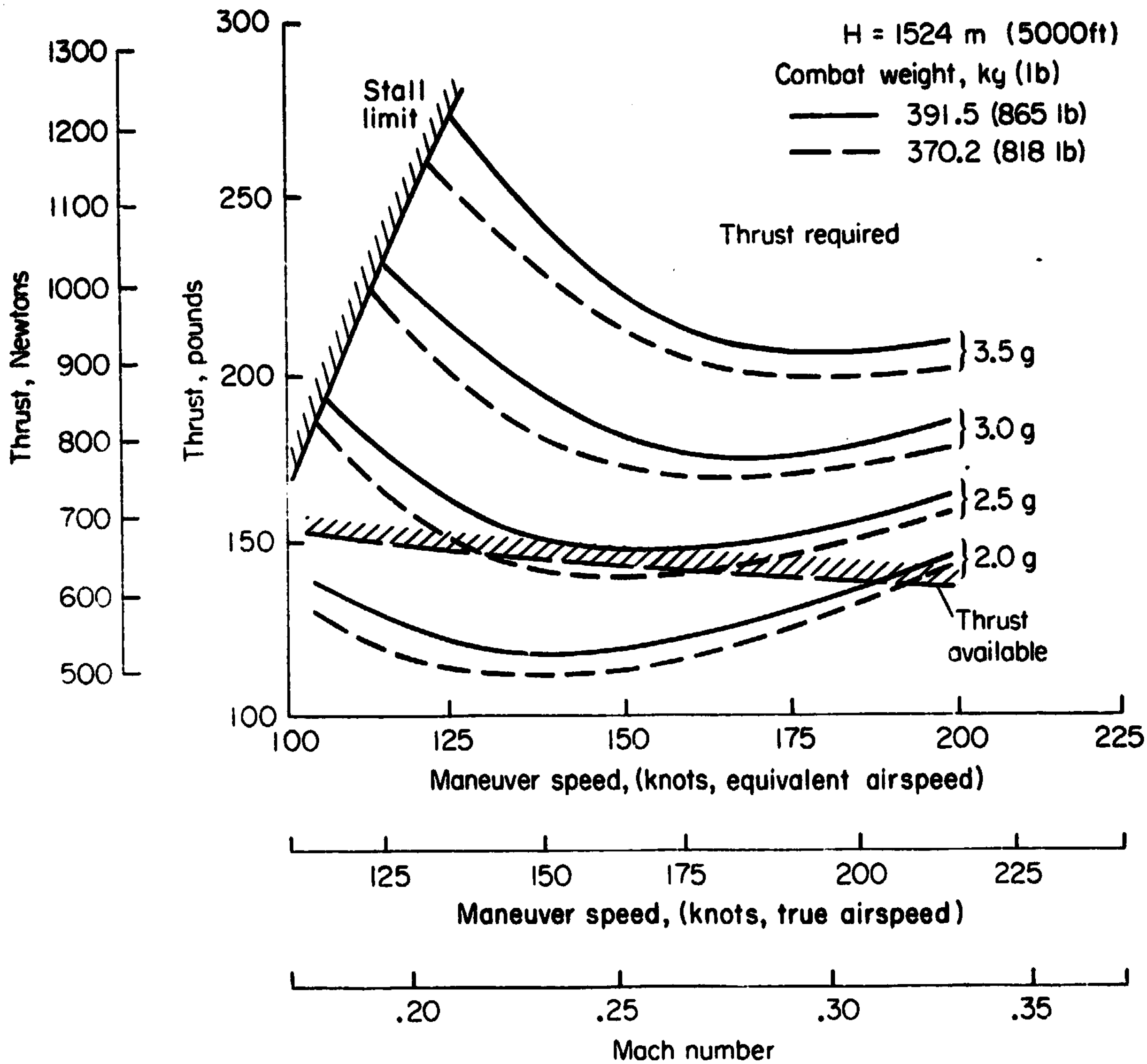

Figure 3.- BD-5J thrust required and available.

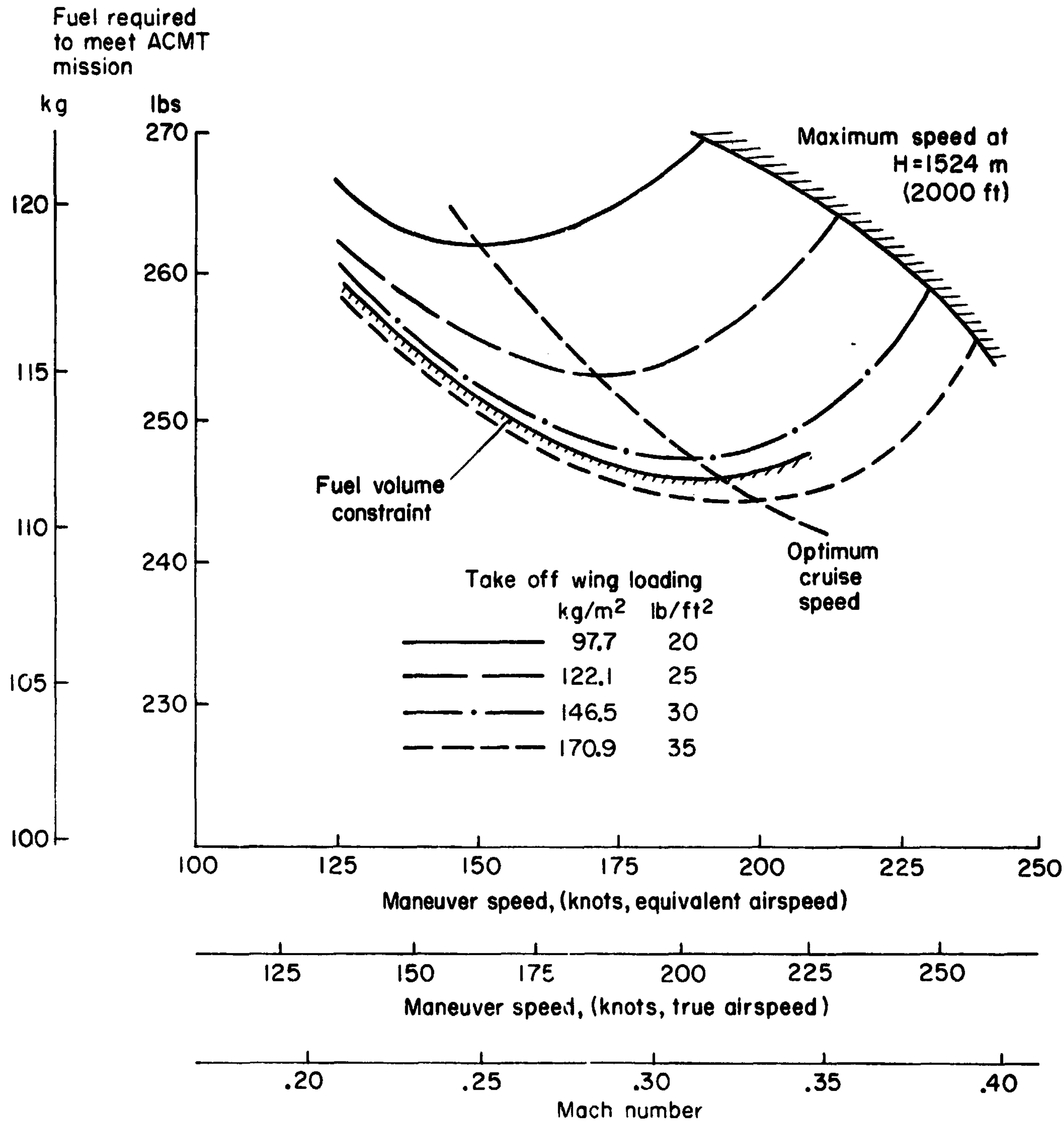

Figure 4.- Fuel-required variations with wing loading and airspeed.

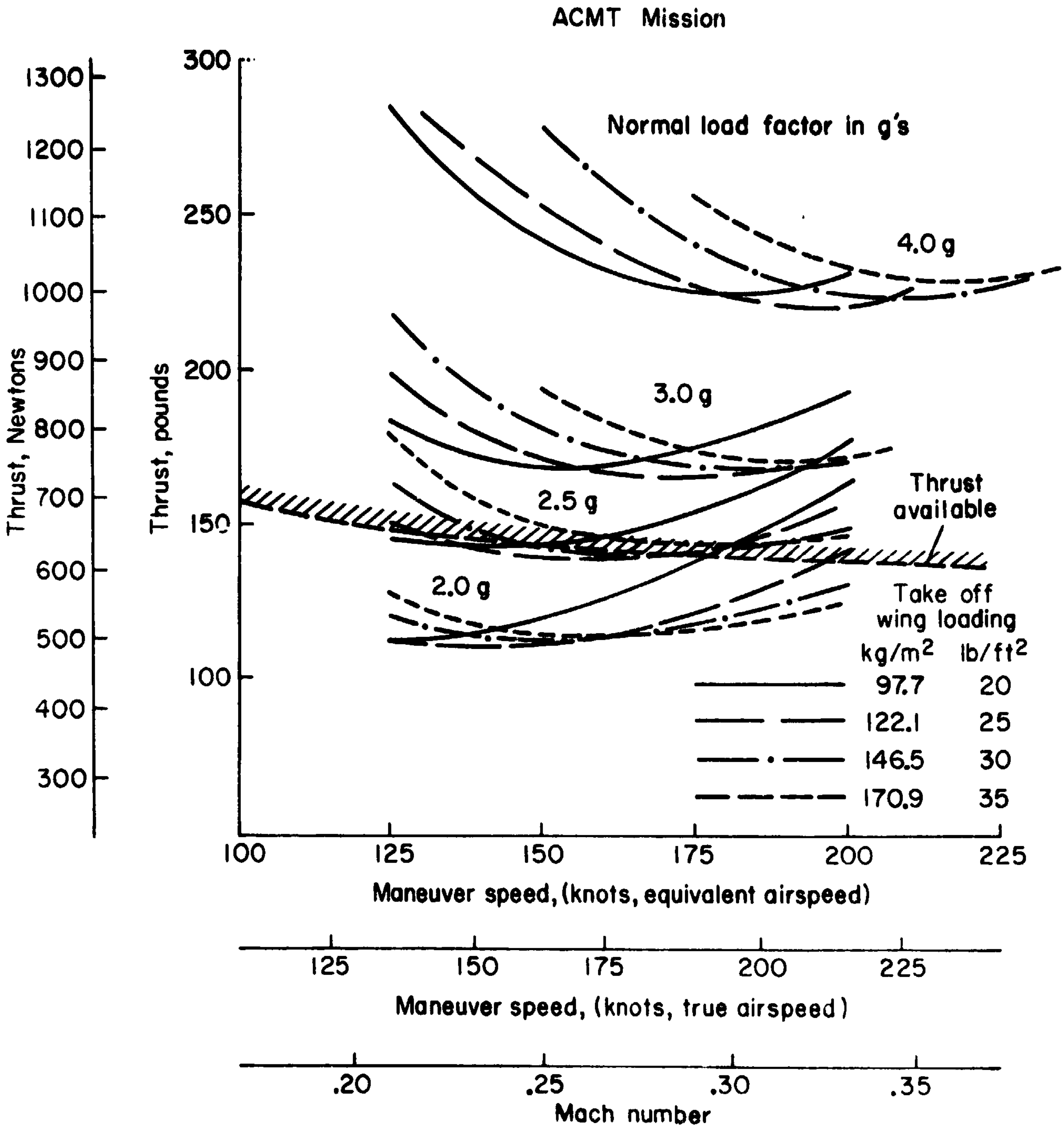

Figure 5.- Thrust required and available for wing-loading variations.

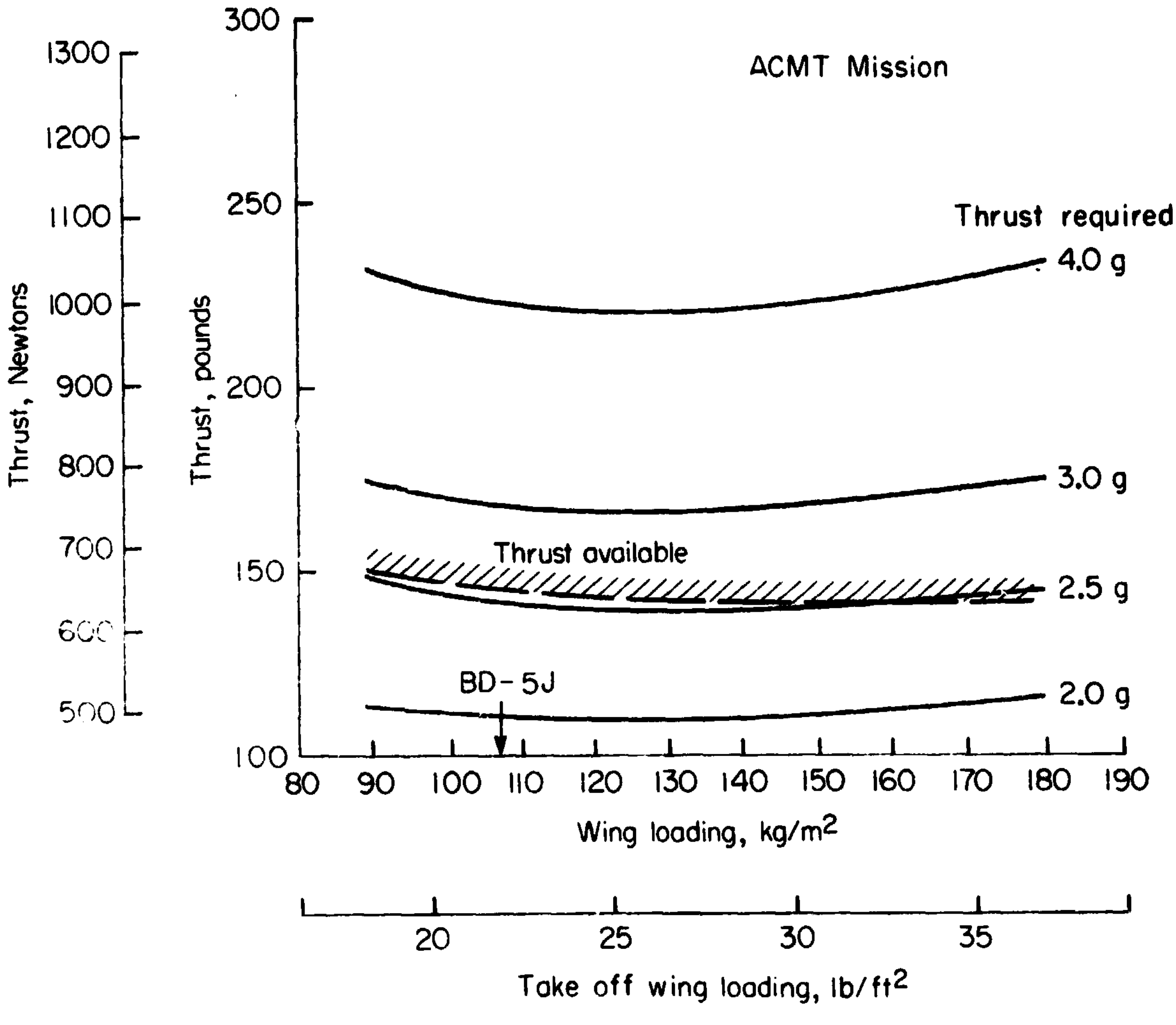

Figure 6.- Thrust required minimized by wing loading.

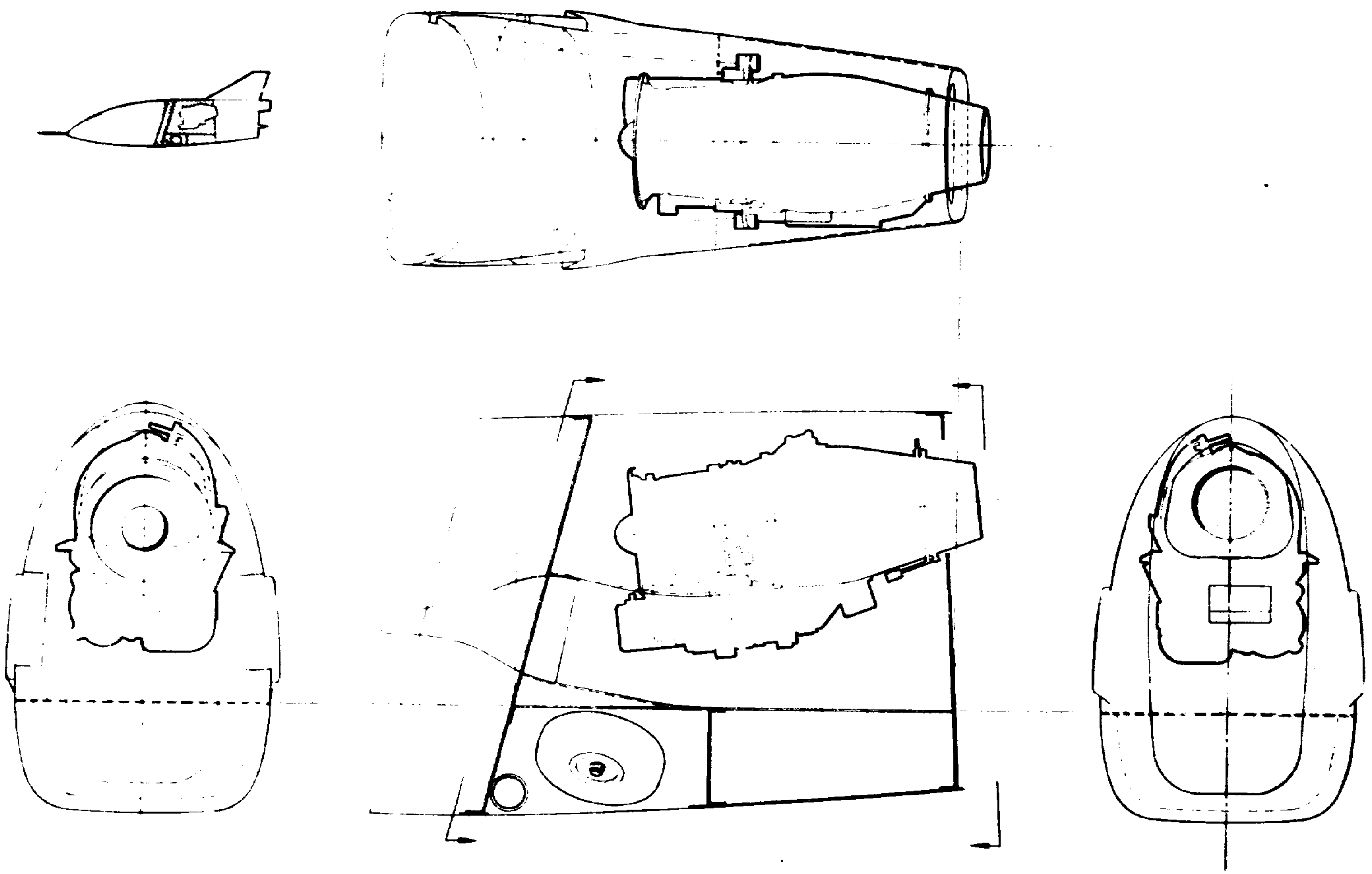

Figure 7.- WR19-3 engine installation.

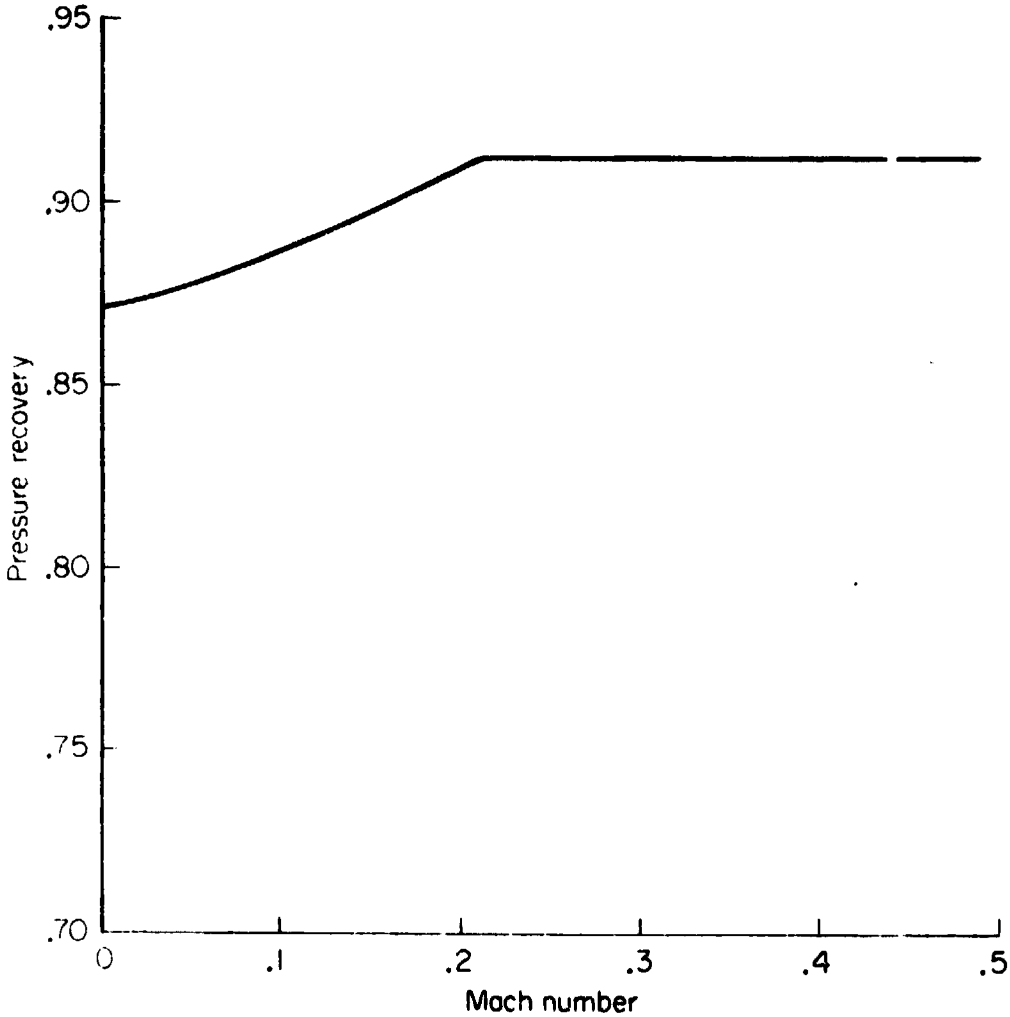

Figure 8.- Inlet pressure recovery.

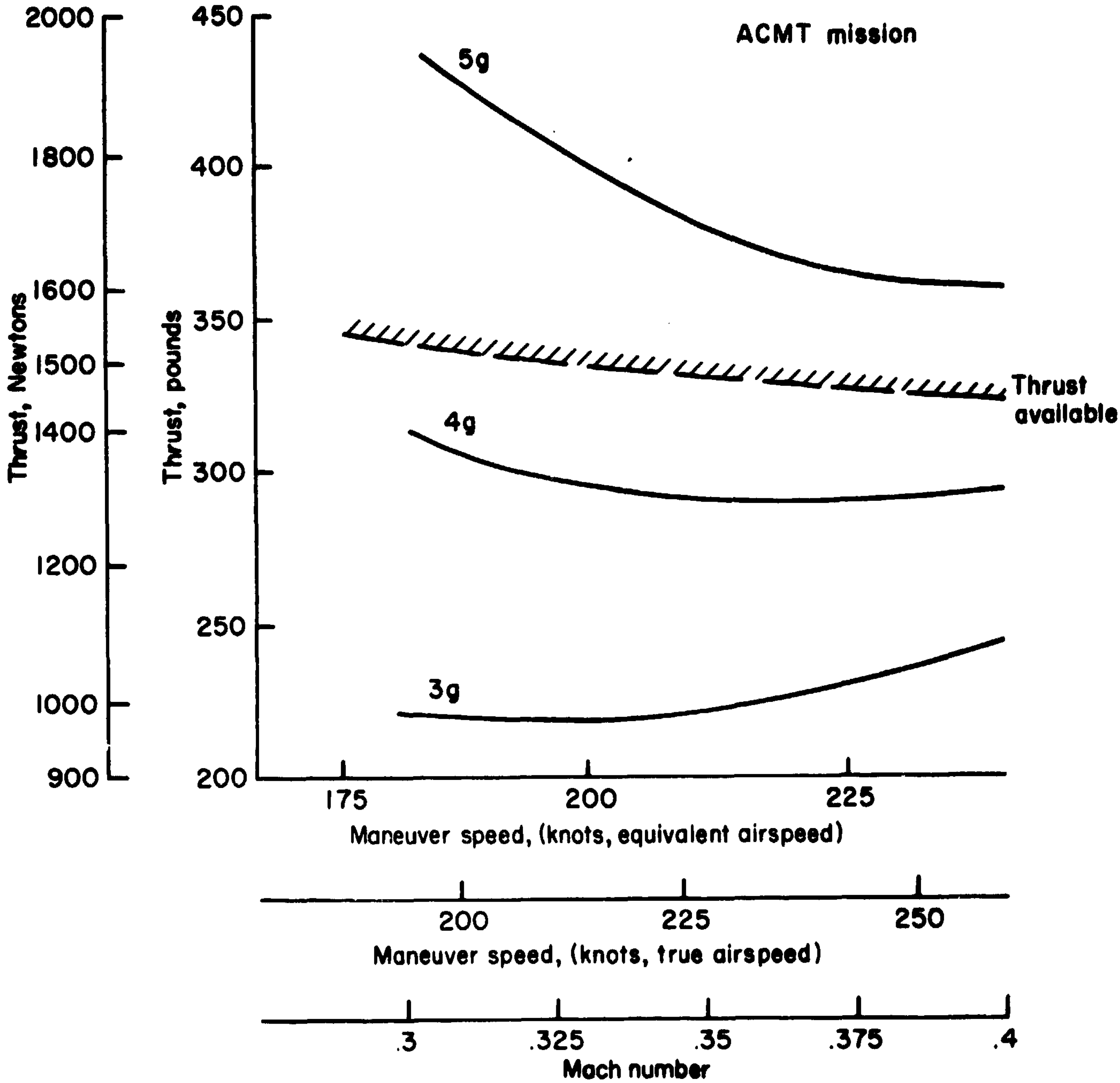

Figure 9.- Thrust required and available with the WR19-3 engine.

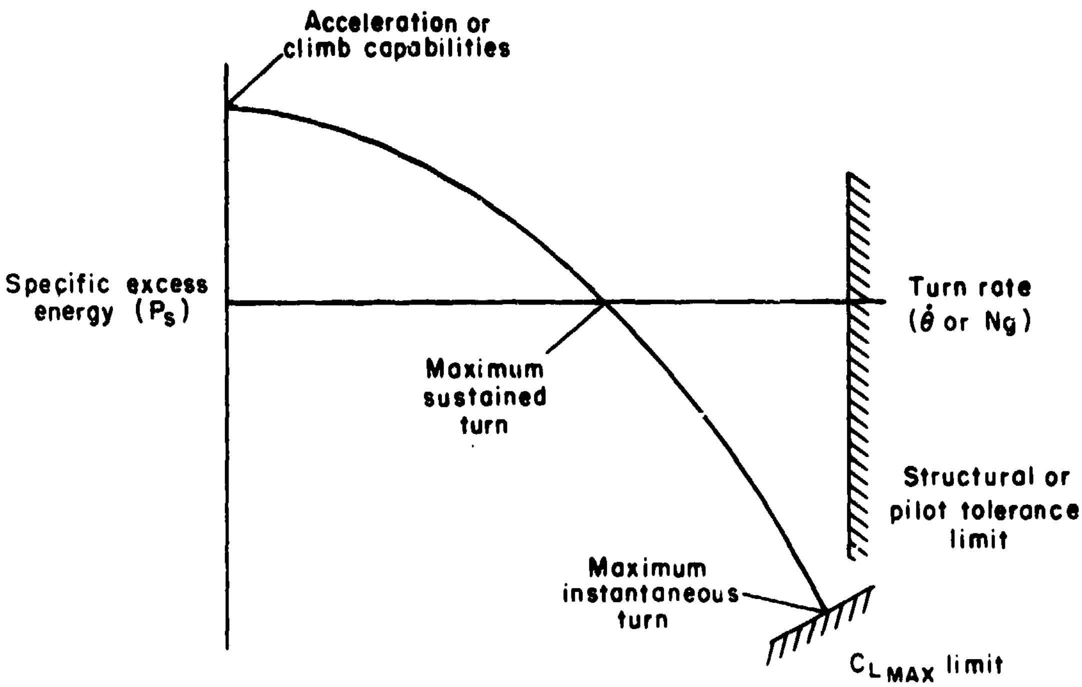

Figure 10.- Specific excess energy versus load factor.

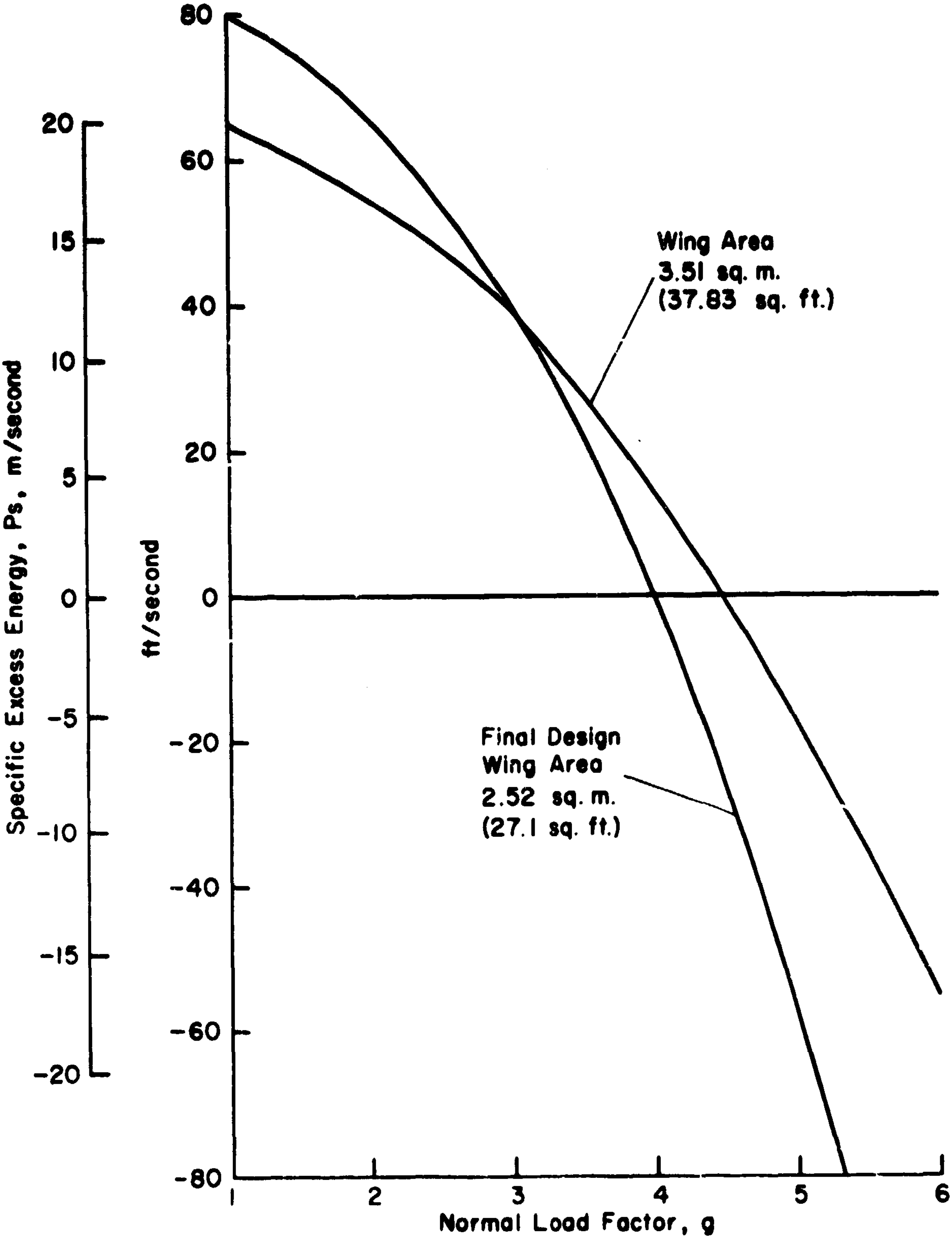

Figure 11.- Specific excess energy with reduced wing area.

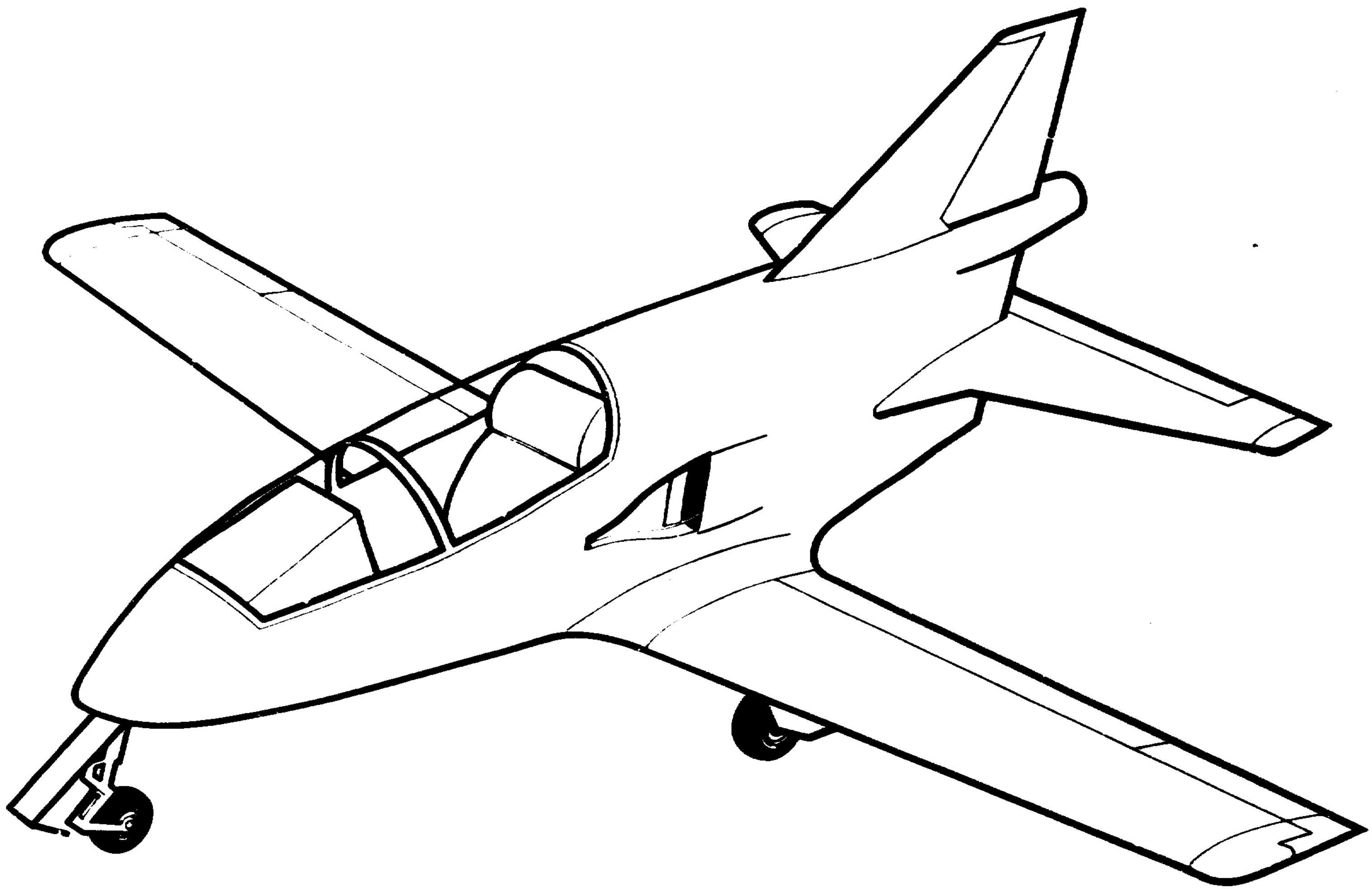

Figure 12.- Final design.

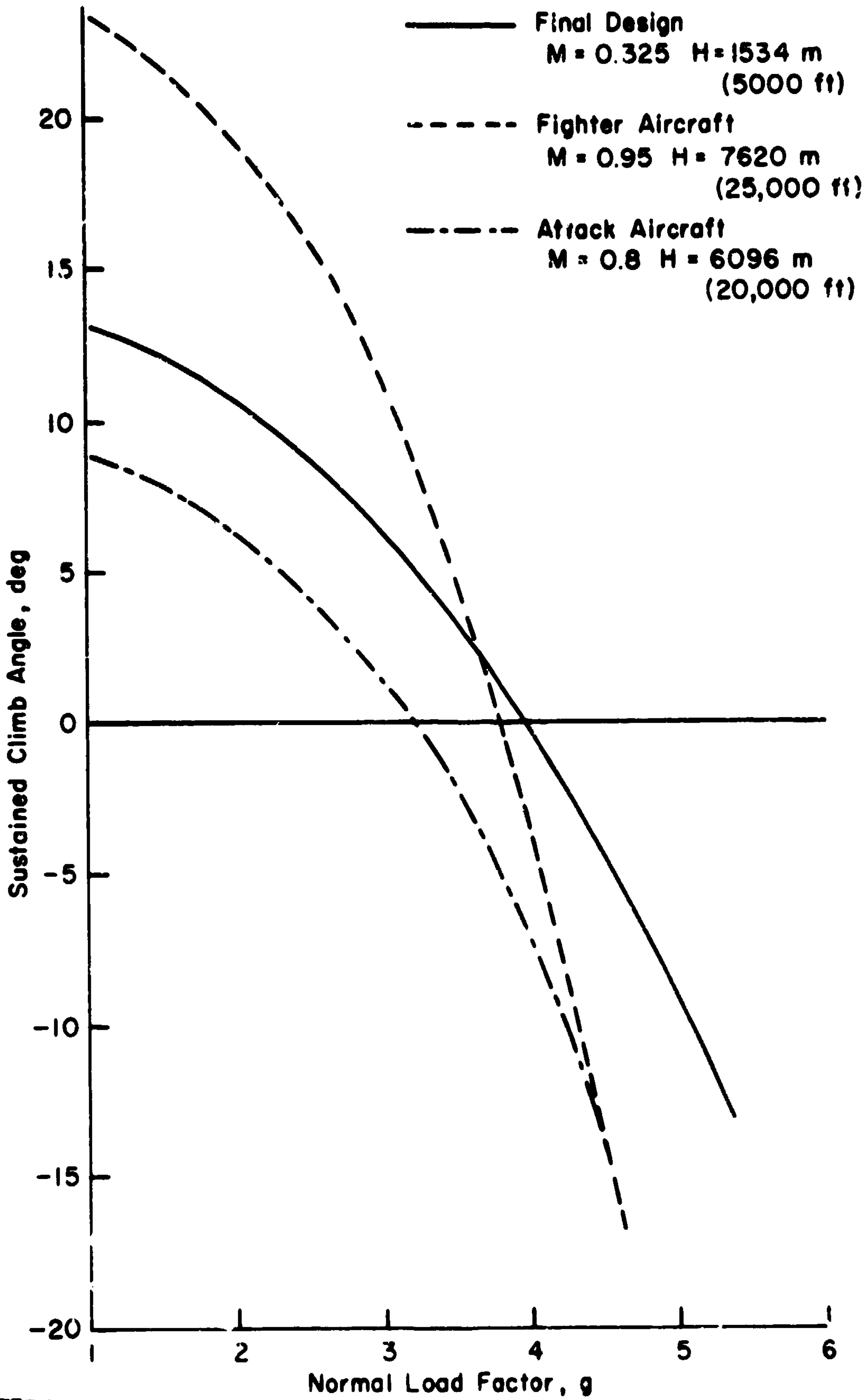

Figure 13.- Sustained climb angle comparisons.

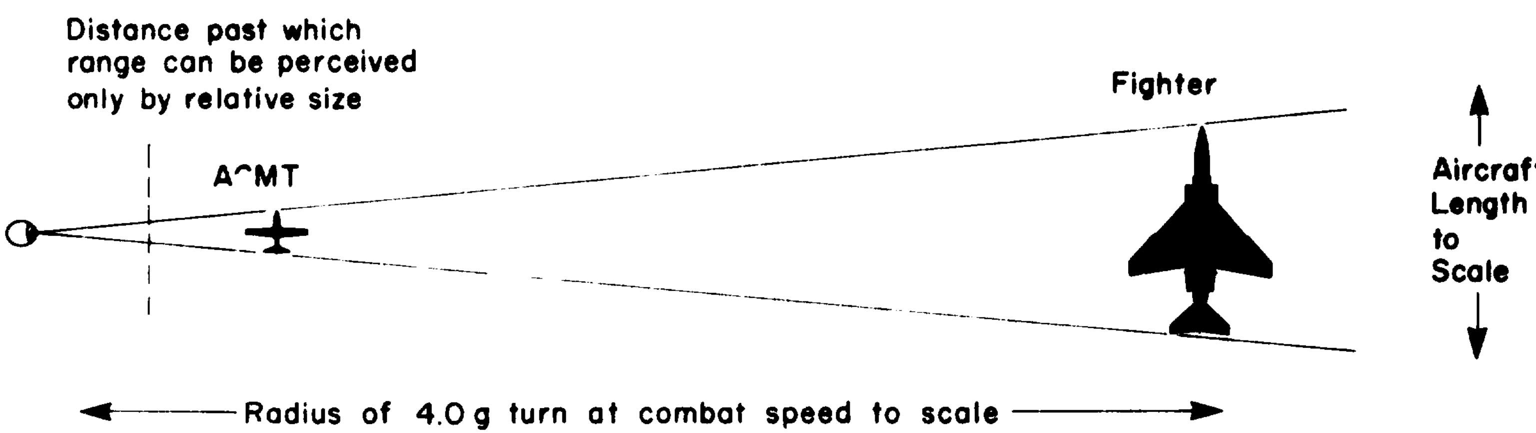

Figure 14.- Visual distance cues.

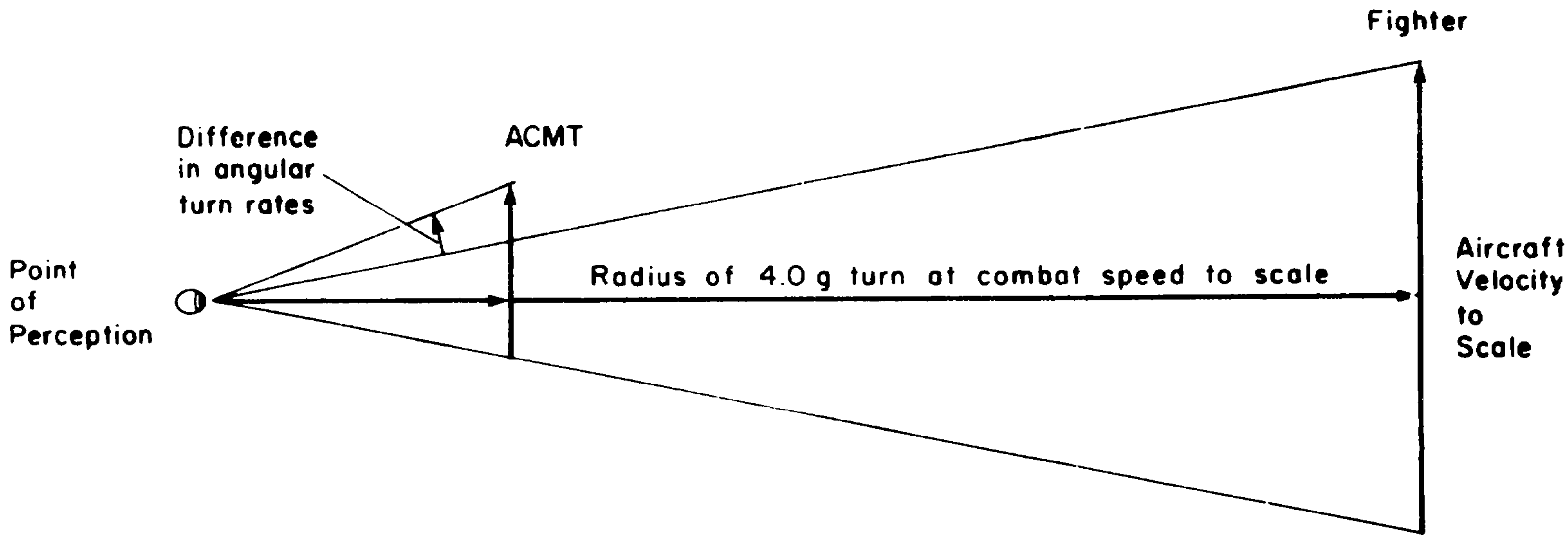

Figure 15.- Relative angular rates.